

# THE MAX AND MAXIMA EXPERIMENTS

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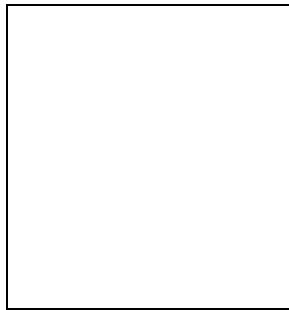
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## Abstract

We summarize the performance of the MAX experiment during its 5 years of operation and present a compilation of the results to date. We describe MAXIMA, a balloon borne experiment employing an array of detectors in the focal plane, that will provide sensitive measurements of the power spectrum between  $l \sim 60$  and  $l \sim 650$ .

## 1 MAX

The Millimeter wave Anisotropy eXperiment (MAX) was a balloon borne experiment that measured the cosmic microwave background anisotropy (CMBA) on half degree angular scale from 1989 to 1994. It was a collaboration between groups in the University of California, Santa Barbara and Berkeley. Between 1989 and 1994 the instrument was launched 5 times and scanned 9 regions of the sky for CMBA. First detection of CMBA signals was reported by Alsop *et al.* [1]. Table 1 summarizes the flights, the regions scanned, flat band power results, and CMBA papers published.

### 1.1 Overview of the MAX experiment

Several papers describe the MAX instrument [1, 2, 3], here we only summarize selected aspects of the experiment. Particular details of the experiment, e.g. exact beam size, frequency bands,

and bolometer temperature, where modified during the duration of the program. The numbers that will be quoted here refer to the last flight of the program, MAX-5, unless otherwise noted.

MAX had a single pixel photometer at the focal plane of an off-axis Gregorian telescope. The telescope provided a beam of 0.5 degree FWHM. The beam was split inside the photometer to 4 frequency bands by means of dichroic mesh-filters.

During an observation the beam was modulated on the sky with two frequencies. The secondary mirror modulated the beam sinusoidally, in cross-elevation direction, at a frequency of 5.4 Hz and amplitude of 1.4 deg. Simultaneously the entire gondola was scanned in azimuth at constant velocity at an amplitude of 4 degrees and a frequency of 0.0075 Hz. The center of the gondola scan tracked the location of a bright star for the duration of the observation. The fast secondary mirror chop provided effective discrimination against low frequency electronic noise which had a  $1/f$  knee at  $\sim 3$  Hz. The slow scan enabled the subtraction of temporal variations in the bolometer temperature and the atmosphere brightness.

The MAX detectors were composite bolometers operating at 300 mK for the first three flights and at 85 mK for the last two. The MAX-5 bolometer for the 450 GHz band was background limited. At the lower frequency bands phonon and Johnson noise was dominant. During the duration of the program sensitivity to CMB temperature differences improved significantly. For example, the sensitivity of the 180 GHz channel improved by a factor of 10 from  $\sim 2$  mK $\sqrt{\text{sec}}$  [2] to 0.24 mK $\sqrt{\text{sec}}$  [9].

The optical chop at  $\sim 5$  Hz, which was chosen as an optimum in the trade-off between the bolometer time constants and the onset of low frequency noise, determined MAX's  $l$  space coverage to a single window function. The window function peaked at  $l = 150$  and had half power points at  $l = 72$  and  $l = 248$ .

MAX was calibrated by observing a planet once during the flight and then using a partially reflecting membrane as a transfer standard for additional periodic calibrations. The typical absolute calibration error was 10% which was dominated by uncertainties in the brightness temperature of the planets observed.

## 1.2 MAX results

MAX provided seven detections of CMBA signals at an angular scale of  $\sim 0.5$  degrees. For these seven detections the wide frequency coverage, up to 4 channels between 90 GHz and 450 GHz, enabled unambiguous spectral discrimination against emission from galactic dust. Extrapolation of the fluctuations observed in the 408 MHz Haslam map to the MAX frequency bands, using the expected spectral dependence of either synchrotron or Bremstrahlung radiation, yields a fluctuations' amplitude of typically less than 10% of the amplitude observed. Thus it is unlikely that synchrotron or Bremstrahlung are the dominant source of the detected fluctuations. Searches in available catalogs found no sufficiently intense radio sources in the regions observed. The treatment of potential temporal variations in the signal due to atmosphere variability, beam motion relative to the balloon or earth, moon location, etc. are discussed in the references mentioned in Table 1. Two measurements near the star  $\mu$ -Pegasi, where  $100\mu$  IRAS maps indicate significant dust contrast, were expected to reveal dust signals. Indeed, the dust signature detected was morphologically consistent with IRAS. Only upper limits on the CMB fluctuation power were derived in these regions.

Most cosmological models predict an increase in the power spectrum of the CMB fluctuations near the peak of MAX's window function. The MAX results are suggestive of a combined flat band power larger than that detected by the COBE/DMR experiment. Statistical analysis to combine the seven detections to a single estimate of the CMB fluctuation power within MAX's window function is in progress.

Flight/Year/ Region Observed	$(\Delta T/T)_{flat}$	Publication
MAX-1 / 1989		Fischer <i>et al.</i> 1992 [2]
MAX-2 / 1990 / GUM*	$2.9^{+4.3}_{-1.8}$	Alsop <i>et al.</i> 1992 [1]
MAX-3 / 1991 / GUM*	$2.7^{+1.1}_{-0.7}$	Gundersen <i>et al.</i> 1993 [4]
MAX-3 / 1991 / $\mu$ -Pegasi	$< 1.6$	Meinhold <i>et al.</i> 1993 [5]
MAX-4 / 1993 / GUM*	$2.0^{+0.6**}_{-0.4}$	Devlin <i>et al.</i> 1994 [6]
MAX-4 / 1993 / $\sigma$ -Herculis	$1.8^{+0.8**}_{-0.6}$	Clapp <i>et al.</i> 1994 [7]
MAX-4 / 1993 / $\iota$ -Draconis	$1.9^{+0.7**}_{-0.4}$	Clapp <i>et al.</i> 1994 [7]
MAX-5 / 1994 / HR5127	$1.2^{+0.4}_{-0.3}$	Tanaka <i>et al.</i> 1996 [8]
MAX-5 / 1994 / $\phi$ -Herculis	$1.9^{+0.7}_{-0.4}$	Tanaka <i>et al.</i> 1996 [8]
MAX-5 / 1994 / $\mu$ -Pegasi	$< 1.3$	Lim <i>et al.</i> 1996 [9]

Table 1: Summary of MAX results. Values of  $\Delta T/T$  are for flat band  $\langle \frac{l(l+1)C_l}{2\pi} \rangle^{1/2}$ , 95% confidence interval. (\*) GUM stands for the region near the star Gamma Ursae Minoris. (\*\*) Original results were revised as described by Tanaka *et al.* (1996).

## 2 MAXIMA

The goal of next generation experiments is to make precise measurements of the CMBA power spectrum. Theoretical work within the last several years has demonstrated that the optimal observing strategy to constrain the power spectrum, in the absence of systematic errors or foregrounds, is to observe as many sky pixels as possible with modest ( $\sim 1$ ) signal to noise per pixel [10]. It has also been argued that small to intermediate scale measurements, at  $100 \lesssim l \lesssim 1500$  covering the region where CDM models predict adiabatic peaks, could discriminate between various cosmological models [11, 12] and provide information about the cosmological parameters independent of the underlying cosmological model [13].

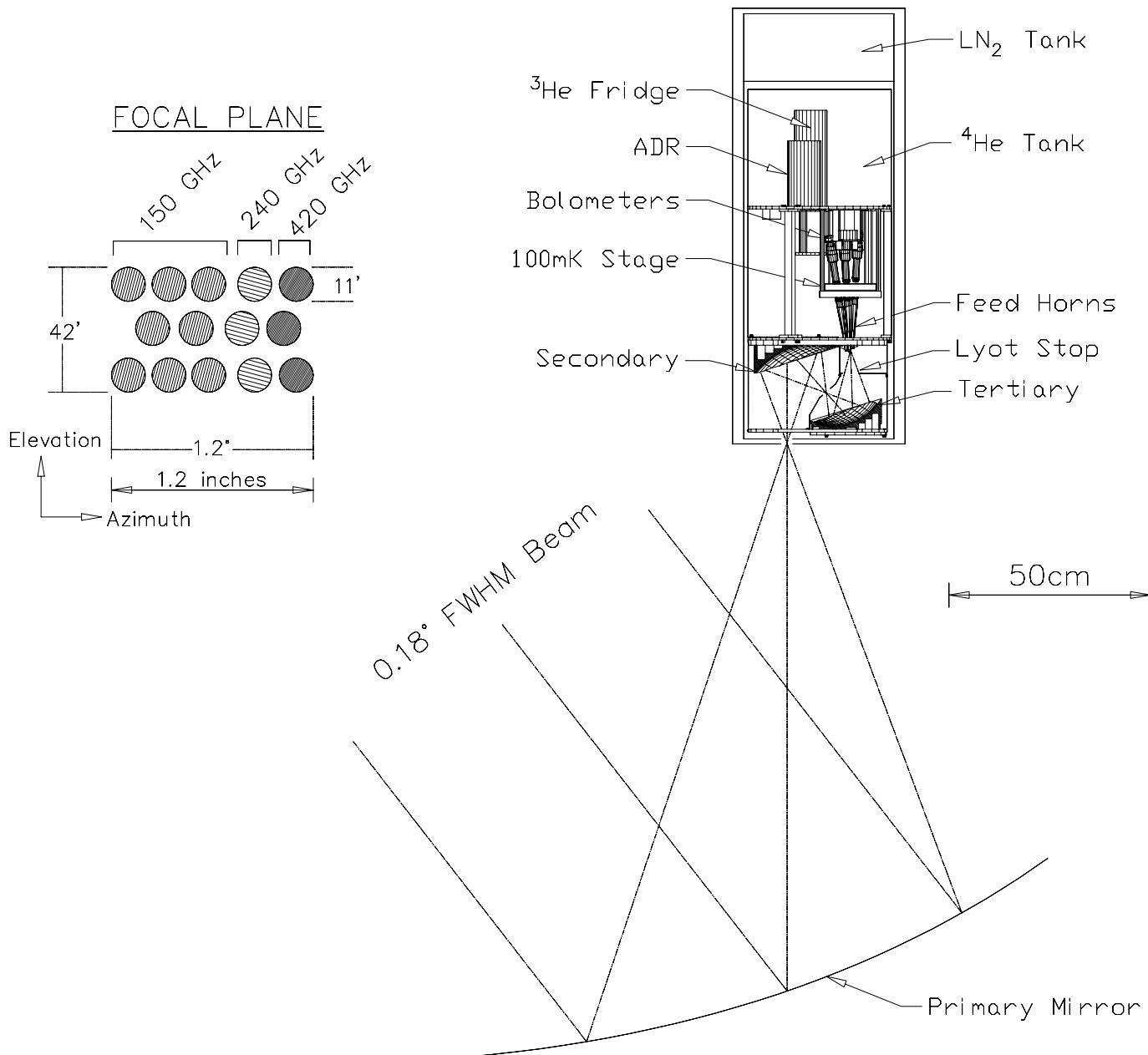
The Millimeter wave Anisotropy eXperiment Imaging Array (MAXIMA) was designed to address these scientific requirements by scanning many pixels on the sky within a single flight, providing large  $l$  space coverage and high  $l$  resolution, while improving on the systematic-error rejection achieved for MAX. MAXIMA is a balloon borne program designed to constrain the CMBA power spectrum on a range of angular scales between  $l \sim 60$  and  $l \sim 650$ . It is a collaboration between groups at the University of California, Berkeley, University of Rome, IROE – Florence, Queen Mary and Westfield College – London, and the California Institute of Technology.

### 2.1 Experimental Configuration

MAXIMA will observe 14 sky pixels simultaneously with 0.18 degree FWHM beams. The attached Figure shows the experiment, the focal plane and its orientation on the sky. The 14 single frequency photometers detect radiation in three frequency bands centered around 150 GHz, 240 GHz, and 420 GHz. The bolometers will be maintained at 100 mK to provide high sensitivity and short time constants. The experiment is designed for up to 24 hour of observations and it will fly in north America.

**2.1.1 optics** The optical system is a three mirror off-axis f/1.8 Gregorian telescope. The primary mirror is a 1.3 meter diameter off axis section of a parabola. The secondary and tertiary mirrors (21 cm and 18 cm in diameter respectively) are conic sections with aspheric components which compensate the aberrations introduced by the primary mirror. The secondary and

# The MAXIMA Experiment



tertiary mirrors and a Lyot stop are mounted in a well baffled box inside the cryostat and are cooled to liquid helium temperature. The cold Lyot stop provides excellent sidelobe rejection and cooling the secondary optics reduces the optical loading on the bolometers. A three mirror system was designed to provide for a diffraction limited  $\sim 1 \times 1 \text{ deg}^2$  field of view at 150 GHz. The secondary and tertiary mirrors are fixed and the light, 11 kg, primary mirror can be modulated around the optical axis of the telescope (the line connecting the center of the primary and the center of the secondary).

**2.1.2 Cryogenics, Detectors and Electronics** The cryostat was designed for a north-American flight of up to 24 hours. The bolometers will be cooled to 100 mK by means of an adiabatic demagnetization refrigerator (ADR). The heat of magnetization generated during the ADR cycle will be sunk into a  $^3\text{He}$  refrigerator operating at 300 mK with a cooling capacity of 25 Joules. The resulting cooling capacity of the ADR is 93 mJoules. With expected heat loads both the ADR and the  $^3\text{He}$  refrigerator will maintain cooling capacity much longer than the cryostat.

Spider-web bolometers [15] operating at 100 mK will be used to detect the incoming radiation<sup>1</sup>. Extrapolation from measurements at 300 mK, and preliminary measurements at 100 mK, indicate that the detectors will be background limited and will have time constants  $\lesssim 10$  msec. We expect a detector NET of  $60 \mu\text{K}\sqrt{\text{sec}}$  ( $90 \mu\text{K}\sqrt{\text{sec}}$ ) at the 150 GHz (240 GHz) frequency band.

The detectors will be AC-biased at a frequency of several hundred Hz<sup>1</sup>. The post lock-in noise of the readout electronics was measured to be less than  $10 \text{ nV}\sqrt{\text{Hz}}$ , down to frequencies smaller than 100 mHz.

**2.1.3 Gondola and Attitude Control** The gondola provides for pointing in azimuth and elevation. Pointing control is achieved with a 5 Hz feedback loop control relying on a two axis magnetometer for coarse pointing ( $\pm 2$  degrees) and on a CCD camera as a fine sensor. The CCD camera and its associated f/0.7 lens provide a field of view of 7.4 degrees in azimuth and 5.5 degrees in elevation, and pixel resolution of 0.8 arcmin/pixel and 0.9 arcmin/pixel, respectively. The on board image processing is expected to provide sub-pixel resolution. Overall pointing stability is expected to be 1 arcminute RMS or better.

## 2.2 Observing Strategy and $l$ Space Coverage

MAXIMA's beam will be scanned in azimuth with two frequencies. The primary mirror will modulate the beam in a triangular wave with frequency  $f_1$  and amplitude  $A_1$ , while the gondola will be simultaneously scanned in azimuth at a slower rate. Here we discuss the choice of  $f_1$  and  $A_1$ .

A bolometer with time constant  $\tau$  acts as a single pole low pass filter on the detected optical signals. The -3 dB point of this filter is used to set a criterion on the maximum speed that the beam can be scanned across the sky. The signal detected by a fast bolometer ( $\tau \simeq 0$ ) when a Gaussian beam with width  $\sigma = 0.425 \times \text{FWHM}$  crosses a point source at constant speed  $\dot{\theta}$  has a Gaussian frequency distribution with width  $\tilde{\sigma} = \dot{\theta}/(2\pi\sigma)$ . If we require that the -3 dB roll-off of a real bolometer will be larger than  $3\tilde{\sigma}$  we obtain a relation between the maximum scan speed and the bolometer time constant

$$\frac{1}{2\pi\tau} \geq \frac{3\dot{\theta}}{2\pi\sigma} \Rightarrow \dot{\theta} \leq \frac{\sigma}{3\tau} = \frac{\text{beam FWHM}}{7\tau}. \quad (1)$$

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<sup>1</sup>See also a paper by Debernardis in these proceedings. The bolometers, readout electronics, and attitude control system are shared technology between BOOMERanG and MAXIMA.

For a 0.18 degrees FWHM beam width and  $\tau = 10$  msec,  $\dot{\theta} \leq 2.6$  degrees/sec. By moving the beams across the sky at this (or somewhat lower) speed the bolometers remain sufficiently sensitive to all spatial frequencies up to  $\sim 1/\text{beam size}$ .

The amplitude  $A_1$  is determined by requiring that the scan frequency  $f_1$  be higher than the knee of the  $1/f$  noise. preliminary measurements during the first flight of MAXIMA suggest that  $f_1 \simeq 0.5$  Hz is appropriate. For a triangular wave

$$4A_1f_1 = \dot{\theta} \leq 2.6 \text{ deg/sec}, \quad (2)$$

so that  $A_1 = 1.3$  degrees. Larger amplitudes are possible with shorter bolometer time constants.

This scan strategy is efficient and enables the synthesis of multiple window functions in a single scan. In combination with the 11 arcminute beams we expect an  $l$  space coverage between  $l = 60$  and  $l = 650$ . (see also a companion paper in this proceedings [16].)

## 2.3 Status and Flight Program

The MAXIMA set of measurements is being comissioned in stages. In the first flight, which was launched from Palestine, Texas, on Sept. 2, 1995, we flew the single beam receiver used on MAX-4, and MAX-5. Most other flight systems, including the gondola, the pointing system, AC-bias electronics, and chopping primary mirror, were new. The flight goals were to test all new flight systems, scan regions of the sky for CMBA signals, and test new scan strategies. All of these have been successfully accomplished. Data analysis is in progress.

The 14-beam array is presently under construction and is scheduled to be launched as MAXIMA-2 in the spring of 1997.

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